

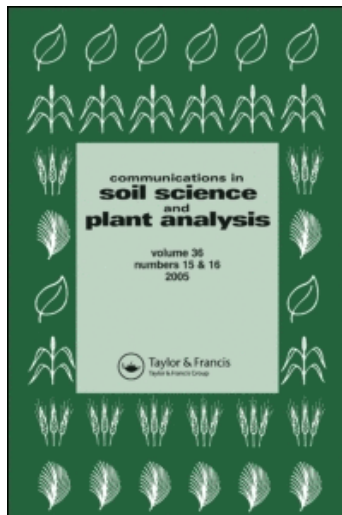
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## LOWLAND RICE RESPONSE TO NITROGEN FERTILIZATION

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### ABSTRACT

Nitrogen deficiency is one of the most important nutritional disorders in lowland rice producing areas around the world. Nitrogen fertilizer recommendations for lowland rice (*Oryza sativa* L.) varieties grown on Inceptisols are limited. The objective of this study was to evaluate the response of lowland rice (cv. Metica 1) to added N and to determine N use efficiency and nutrient accumulation during the crop growth cycle. A field experiment was conducted during 3 consecutive years in the central part of Brazil on a Haplaquept Inceptisol. Nitrogen levels used were 0, 30, 60, 90, 120, 150, 180, and 210 kg N ha<sup>-1</sup>. Nitrogen fertilization significantly increased dry matter and grain yield. Ninety percent of the maximum grain yield (6400 kg ha<sup>-1</sup>) was obtained with the application of 120 kg N ha<sup>-1</sup> in the first year of experimentation. In the second and third years, 90% of the maximum yields (6345

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and 5203 kg ha<sup>-1</sup>) were obtained at 90 and 78 kg N ha<sup>-1</sup>, respectively. Yield components were also significantly affected by N treatments.

Among yield components, panicle length and panicle number m<sup>-2</sup> had highest correlations with grain yield ( $r=0.70^{**}$  and  $0.78^{**}$ ); maximum grain yield across the 3 years was achieved at about 583 panicles m<sup>-2</sup>. Dry matter production and grain yield at the highest N level (210 kg N ha<sup>-1</sup>) across the 3 years were 9423 and 6389 kg ha<sup>-1</sup>, respectively. At this grain + straw yield, the rice crop accumulated 139 kg N, 26 kg P, 218 kg K, 36 kg Ca, 24 kg Mg, 850 g Zn, 5971 g Mn, 125 g Cu, 4629 g Fe, and 104 g B. Nitrogen use efficiency defined in several ways, decreased with increasing N rates. Agronomic efficiency across 3 years averaged over N rates, was 23 kg of grain produced per kg of N applied. Physiological efficiency was 146 kg biological yield (grain + straw) produced per kg of N accumulated across the 3 year and N rates. Average agrophysiological efficiency was 63 kg grain produced per kg of N accumulated in the grains plus + straw. Apparent N recovery efficiency was 39% across the 3 years and N rates. Average nitrogen utilization efficiency was 58 kg of grain produced per kg N utilized by the rice crop. Soil pH and calcium concentration in the soil decreased significantly at higher N rates, whereas, soil Al<sup>3+</sup> level was significantly increased after the harvest of the third rice crop.

## INTRODUCTION

Rice is the staple food for nearly half of the world's population, most of whom live in developing countries. The crop occupies one-third of the world's total area planted to cereals and provides 35–60% of the calories consumed by 2.7 billion people (1). Modern production agriculture requires efficient, sustainable, and environmentally sound management practices. Nitrogen is normally a key factor in achieving optimum lowland rice grain yields (2). It is, however, one of the most expensive inputs and if used improperly, can pollute the ground water. Although rice is grown in different ecosystems, 78% of the world's rice is grown under irrigated or rainfed lowland conditions (3). Soils under these conditions are saturated, flooded, and anaerobic and N use efficiency is low. Under these situations, increasing rice yield per unit area through use of appropriate N management practices has become an essential component of modern rice production technology.

Nitrogen is the nutrient input normally required in large quantities for production of lowland rice (4) and in Brazilian Inceptisols, it is one of the most yield



limiting nutrients for lowland rice production (2) Fertilizer N use efficiency of lowland rice is relatively low due to loss of applied N through leaching, volatilization and denitrification in the soil-flood water system (5).

Despite the tremendous amount of research on fertilizer based strategies to increase N-use efficiency in lowland rice, the recovery efficiency from applied N fertilizer (plant N/N applied) and the agronomic efficiency (grain yield/N applied) achieved by rice farmers are relatively low. For example, in a study in farmer's field in the Philippines, Cassman et al. (6) reported that only 30–40% of the applied N was accounted for by increased aboveground N accumulation.

Recovery efficiencies of 30–50% of applied N are typical in field experiments at research stations for lowland rice in the tropics with agronomic efficiencies of 15–25 kg grain per kg of applied N depending on season, yield level, and the rate and timing of N application (7,8). This means that improved N fertilizer practices are needed to reduce environmental impacts and increase economic benefits of N fertilization. Selection of the most appropriate rate of N fertilizer is one of the management practices that can affect both economic viability of crop production and impact of agriculture on the environment. Traditionally, the optimum rate of N fertilizer has been the rate that results in maximal economic yield (9). Further, proper timing in combination with adequate rate of N application is crucial to minimize N losses and improve N use efficiency (10).

Rice N requirements are closely related to crop yield levels, which in turn are sensitive to climate, particularly solar radiation and the supply of other nutrients (11). These factors also affect the pattern and quantity of N supplied from indigenous soil resources (5). Fertilizer-N management strategies must therefore be responsive to potentially large variations in crop N requirements and soil N supply (6). Nowadays, the environmental as well as financial impact of N fertilizer use deserves increased attention. The objectives of the current study were 1) to determine lowland rice response to N fertilization, 2) to evaluate N uptake and use efficiency under different N rates and, 3) to determine nutrient accumulation patterns during the crop growth cycle. Results are expected to improve management of N fertilizers and yields of lowland rice.

## MATERIALS AND METHODS

A field experiment involving flooded rice (*Oryza sativa* L.) was conducted during three consecutive years (1995–1996, 1996–1997, and 1997–1998) at the EMBRAPA-National Rice and Bean Research Centers experimental station, Palmital, state of Goiás, central part of Brazil. The soil of the experimental site was an Inceptisol (sandy-clay loam, isothermic, mesic Typic Haplaquepts). The initial soil chemical properties at 0–20 cm soil depth are presented in Table 1. Soil pH



**Table 1.** Chemical and Physical Properties of Low-land Incetisol Before the Application of Nitrogen Treatments

Soil Property	Value
pH in water	5.5
Organic matter (g kg <sup>-1</sup> )	26
P (mg kg <sup>-1</sup> )	19.2
K (mg kg <sup>-1</sup> )	38
Ca (cmol <sub>c</sub> kg <sup>-1</sup> )	3.7
Mg (cmol <sub>c</sub> kg <sup>-1</sup> )	1.7
Al (cmol <sub>c</sub> kg <sup>-1</sup> )	0.3
Cu (mg kg <sup>-1</sup> )	2.9
Zn (mg kg <sup>-1</sup> )	2.9
Fe (mg kg <sup>-1</sup> )	227
Mn (mg kg <sup>-1</sup> )	60
Clay (g kg <sup>-1</sup> )	305
silt (g kg <sup>-1</sup> )	225
Sand (g kg <sup>-1</sup> )	470

was measured in a 2:2.5 soil-water suspension. Phosphorus, K, Cu, Zn, Fe, and Mn were extracted by the Mehlich 1 extracting solution (0.05 M HCl + 0.0125 M H<sub>2</sub>SO<sub>4</sub>). Phosphorus was determined colorimetrically and K, Cu, Zn, Fe, and Mn by atomic absorption spectroscopy. Calcium, Mg, and Al were extracted with 1 M KCl. Aluminum was determined by titration with NaOH, and Ca and Mg were determined by titration with EDTA. Organic matter was determined by the Walkley-Black method, and soil texture by the pipette method. Soil analysis methods used in this study are described in a soil analysis manual published by EMBRAPA (12).

Treatments consisted of eight N rates: 0, 30, 60, 90, 120, 150, 180, and 210 kg N ha<sup>-1</sup> as ammonium sulfate applied each year. One-third was applied at sowing, and the remainder was topdressed twice, at equal rates, at 45 and 70 days after sowing (DAS), a standard practice for lowland rice crops under Brazilian conditions (13). Treatments were replicated four times in a randomized block design. Plot size was 5 by 4 m with a 2 m alley between plots. All plots were surrounded by soil levees 30 cm high to avoid N contamination between plots. Replicates were separated by 6 m alleys and by bunds and canals. The experimental area received 52 kg P ha<sup>-1</sup> as triple superphosphate, and 66 kg K ha<sup>-1</sup> as potassium chloride as basal fertilizers in bands at the time of sowing each year. These basal fertilizer treatments are based on earlier work (14). Flooded rice cultivar Metica 1, recommended by the National Rice and Bean research center for central Brazil, was planted manually at a spacing of 20 cm between rows, using 100 seeds



per meter row. This quantity of seeds is adequate for lowland rice in central Brazil (15).

In the first year, sowing was done on 17 October 1995 and the crop was harvested on 6 March 1996. In the second year sowing was done on 21 October and harvesting was done on 10 March 1997 and in the third year sowing was done on 16 October and harvesting on 3 March 1998. Rice plots were flooded about 30 DAS to a depth of 10 to 15 cm of standing water, remained flooded during the crop growth period, and drained 1 week before harvest. Plant samples were taken from a 1-m long row in each plot at initiation of tillering (IT), active tillering (AT), panicle initiation (PI), booting (B), flowering (F), and at physiological maturity (PM) during each year to determine dry matter production and nutrient accumulation. Tiller numbers were counted in 1m rows at four places in each plot at these growth stages. Panicle numbers were also counted at four places in 1-m meter rows in each plot at harvest. The area harvested from each plot for grain determination was 4 by 2.4 m. Dried plant material was ground and digested with a 2:1 mixture of  $\text{HNO}_3$  and  $\text{HClO}_4$ . Phosphorus was determined colorimetrically, and all other nutrients were determined by atomic absorption spectroscopy (16). Total N in the plant tissue was determined with a Tecator 1016 digester and 1004 distilling unit. About 2 weeks after harvesting the 3rd crop, soil samples were taken at 0–20 cm soil depth from each plot to determine chemical properties. About 30 cores were taken from each plot to make one composite sample. Soil samples were dried and ground, and chemical properties were determined by methods described in the manual of soil analysis of EMBRAPA (12).

Nitrogen use efficiencies were calculated using the following formulas (2):

$$\text{Agronomic efficiency (AE)} = (G_f - G_u / N_a) = \text{kg kg}^{-1}$$

where  $G_f$  is the grain yield of the fertilized plot (kg),  $G_u$  is the grain yield of the unfertilized plot (kg), and  $N_a$  is the quantity of N applied (kg).

$$\text{Physiological efficiency (PE)} = (Y_f - Y_u / N_f - N_u) = \text{kg kg}^{-1}$$

where  $Y_f$  is the total biological yield (grain plus straw) of the fertilized plot (kg),  $Y_u$  is the total biological yield of the unfertilized plot (kg),  $N_f$  is the nutrient accumulation of the fertilized plot (kg), and  $N_u$  is the nutrient accumulation of the unfertilized plot (kg).

$$\text{Agrophysiological efficiency (APE)} = (G_f - G_u / N_{tf} - N_{tu}) = \text{kg kg}^{-1}$$

where  $G_f$  is the grain yield of the fertilized plot (kg),  $G_u$  is the grain yield of the unfertilized plot (kg),  $N_{tf}$  is the N accumulation by straw and grains in the fertilized plot (kg), and  $N_{tu}$  is the N accumulation by straw and grains in the unfertilized plot (kg).

$$\text{Apparent recovery efficiency (ARE)} = (N_f - N_u / N_a) \times 100 = \%$$



where  $N_f$  is the N accumulation by the total biological yield (straw plus grain) in the fertilized plot (kg),  $N_u$  is the N accumulation by the total biological yield (straw plus grain) in the unfertilized plot (kg), and  $N_a$  is the quantity of N applied (kg).

$$\text{Utilization efficiency (EU)} = \text{PE} \times \text{ARE} = \text{kg kg}^{-1}$$

All the data were analyzed by analysis of variance, and regression analysis was used to test treatment effects. Appropriate regression equations were selected on the basis of probability level significance and higher  $R^2$  values.

## RESULTS AND DISCUSSION

### Grain Yield and Yield Components

Significance of F values derived from analysis of variance showed significant responses of rice grain yield and yield components to N rates and years of cultivation but year  $\times$  nitrogen rate ( $Y \times N$ ) interactions were significant only for grain yield (Table 2). Therefore, grain yield data of three years as well as average values of 3 year are presented. Grain yield increased with N fertilization and showed significant ( $P < 0.01$ ) quadratic responses in the 3 years experimentation (Fig. 1). Based on regression equations, in the first year, maximum grain yield ( $6937 \text{ kg ha}^{-1}$ ) was obtained at  $209 \text{ kg N ha}^{-1}$ , in the second year maximum grain yield ( $6958 \text{ kg ha}^{-1}$ ) was obtained at  $163 \text{ kg N ha}^{-1}$ , and in the third year maximum grain yield of  $5682 \text{ kg ha}^{-1}$  was obtained at  $149 \text{ kg N ha}^{-1}$ . The average data of 3 years showed that maximum grain yield of  $6465 \text{ kg ha}^{-1}$  was obtained with the application of  $171 \text{ kg N ha}^{-1}$ . Singh et al. (17) reported that maximum average grain yield of  $7700 \text{ kg ha}^{-1}$  of 20 lowland rice genotypes was obtained at 150 to  $200 \text{ kg N ha}^{-1}$  at the International Rice Research Institute in the Philippines. Our

**Table 2.** Significance of F Values Derived from Analysis of Variance for Lowland Rice Grain Yield and Yield Components Measured in Three Years at Eight N Rates

Yield and Yield Components	Years	N Rates	$Y \times N$	CV, %
Grain yield	**	**	*	10
No. of panicles	**	**	NS	9
1000-grain wt.	**	*	NS	6
Panicle length	**	**	NS	4
Spikelet sterility	**	NS	NS	17

\*, \*\* Significant at the 0.05 and 0.01 probability levels, respectively.



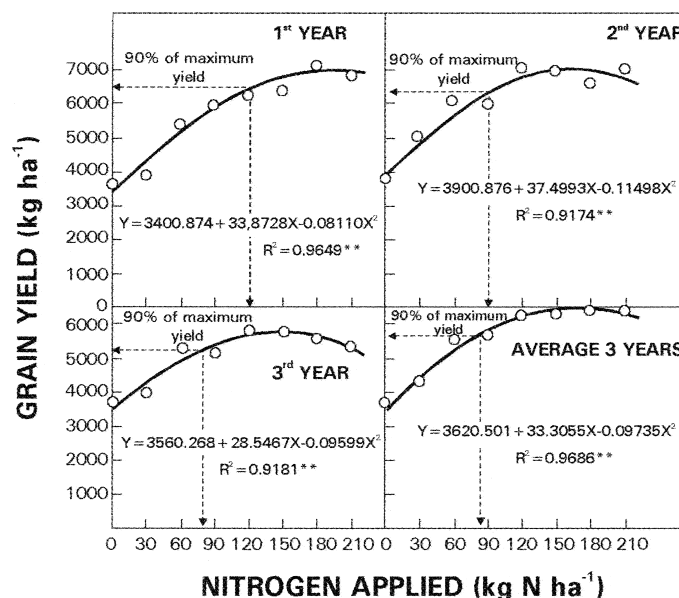


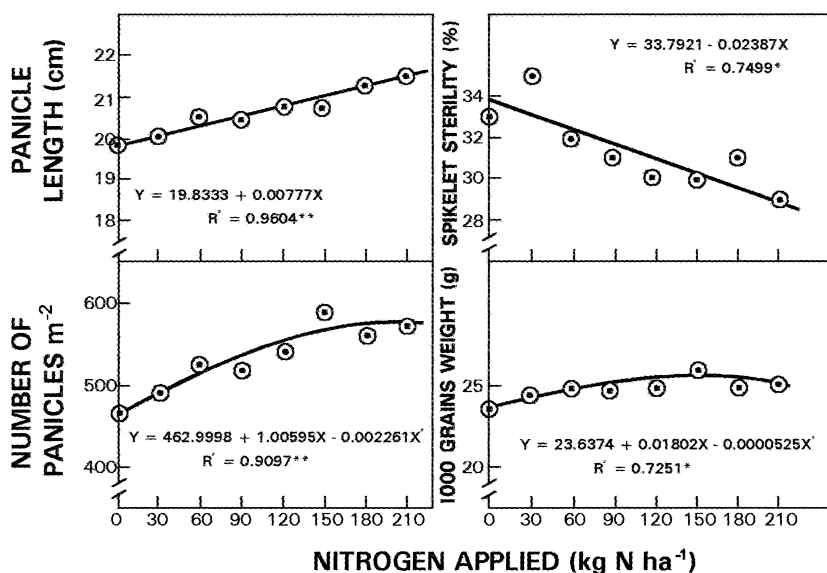
Figure 1. Grain yield of lowland rice as influenced by nitrogen fertilization.

results fall more or less in the same range. In our fertilizer experimentations, however, 90% of maximum yield is considered as an economical rate (18), in the first year it was (6298 kg kg<sup>-1</sup>) achieved at 120 kg N ha<sup>-1</sup>. In the second and third years 90% of the maximum grain yields (6345 and 5203 kg ha<sup>-1</sup>) were achieved at 90 and 78 kg N ha<sup>-1</sup>, respectively. The average of 3 years data showed that 90% of the maximum grain yield (5731 kg ha<sup>-1</sup>) was obtained at 84 kg N ha<sup>-1</sup>. This means, that there was a residual effect of N application in lowland rice grown on an Inceptisol. The increase in grain yield of lowland rice at the economical rate (120 kg N ha<sup>-1</sup>) in the first year was 76% as compared to control N treatment. Similarly, the increase in grain yield in the second and third year at the economical N rates (90 and 78 kg ha<sup>-1</sup>) was 69 and 41%, respectively. The average increase of grain yield across the 3 years was 56% at the economical N rate of 84 kg ha<sup>-1</sup>. At the zero N level, the grain yield was 3579, 3754, and 3702 kg ha<sup>-1</sup> in the first, second and third years, respectively. The average value of grain yield across the 3 years was 3678 kg ha<sup>-1</sup> at zero N rate. This means rice grain yield under the control treatment (no N application) was quite good during three years of experimentation. In control N treatment, rice yields increased during the second and third years of cultivation as compared to the first year of cultivation. Fageria and Baligar (15) also reported significant increases in grain yields of lowland rice



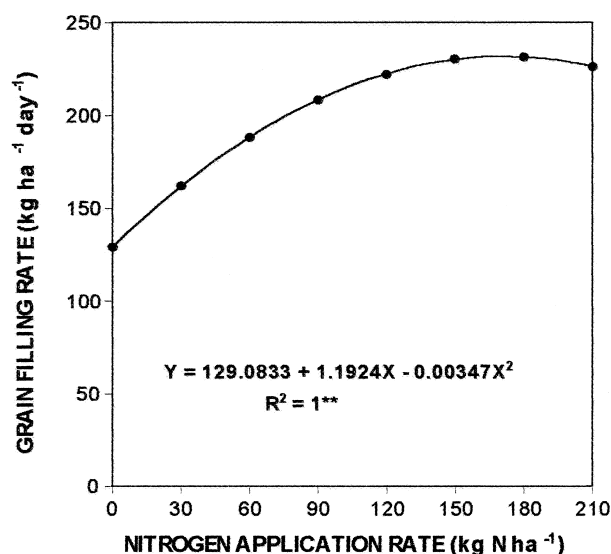
grown on an Inceptisol in the central part of Brazil. These authors reported that an average yield of 3 years (5523 kg ha<sup>-1</sup>) of lowland rice was achieved with the application of 100 kg N ha<sup>-1</sup> and that in grain yields at low fertility level increased with succeeding cropping years.

The Y × N interactions in relation to yield components were not significant (Table 2), therefore, three-year average values of these parameters under different N rates are presented (Fig. 2). Grain yield in rice is a function of panicles per unit area, number of spikelets per panicle, 1000-grain weight and spikelet sterility or filled spikelets (2). Therefore, it is very important to understand the management practices that influence yield components and consequently grain yield. Nitrogen application up to 210 kg ha<sup>-1</sup> influenced panicle length significantly (P < 0.01) and the relationship between N applied and panicle length was linear (Fig. 2). The number of panicles m<sup>-2</sup> and 1000-grain weight were also increased significantly and quadratically with the application of N fertilizer. Spikelet sterility, however, decreased significantly and linearly with increasing N rates. Nitrogen treatment accounted about 96% variation in panicle length, about 91% variation in panicles m<sup>-2</sup>, about 75% variation in spikelet sterility, and about 73% of variation in 1000-grain weight. Yoshida (7) also reported that panicles per unit area, filled spikelet percentage and 1000-grain weight were major contributors to increased



**Figure 2.** Influence of nitrogen fertilization on panicle length, panicle number m<sup>-2</sup>, spikelet sterility, and 1000-grain weight of lowland rice.

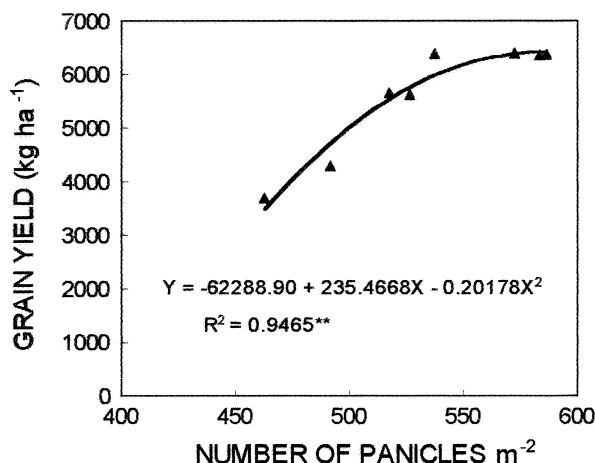




**Figure 3.** Relationship between N rate and grain filling rate in lowland rice across the three years.

grain yield in modern high yielding rice varieties. The increase in panicle length was 9%, increase in panicle number was 24%, increase in 1000-grain weight was 6% and decrease in spikelet sterility was 14% at 210 kg N ha<sup>-1</sup> as compared to control treatment. Low spikelets sterility at high N rate is considered one of the important selection criteria for N responsive rice cultivars (19). Grain filling rate (grain yield/days from flowering to harvest) was significantly affected with N rates (Fig. 3). It was 129 kg ha<sup>-1</sup> day<sup>-1</sup> at zero N rate and increased to 231 kg ha<sup>-1</sup> day<sup>-1</sup> (maximum value) at 180 kg N ha<sup>-1</sup> rate. The relationship between number of panicles m<sup>-2</sup> and grain yield was highly significant ( $P < 0.01$ ) and quadratic; 583 panicles m<sup>-2</sup> are optimal to produce a grain yield of about 6400 kg ha<sup>-1</sup> under the existing experimental conditions (Fig. 4). Correlation coefficients between grain yield and these four yield components were also determined (Table 3). Numbers of panicles m<sup>-2</sup> were significantly correlated with grain yield in 3 years, whereas, 1000-grain weight and panicle length were also significantly correlated with grain yield, but only in two years. Spikelet sterility was having significant and negative correlation with grain yield in two years of study. Panicle numbers, however, had highest correlation with grain yield, followed by panicle length. This means that it is possible to manipulate these yield components with N treatments in favor of higher grain yield in lowland rice.





**Figure 4.** Relationship between number of panicles and grain yield of lowland rice. Data are averages for 3 years.

**Table 3.** Correlation Coefficients (R-Values) Between Lowland Rice Grain Yield and Yield Components

Yield Components	Correlation Coefficient r		
	1 <sup>st</sup> Year	2 <sup>nd</sup> Year	3 <sup>rd</sup> Year
No. of panicles	0.78 **	0.50 **	0.44 *
1000-grain wt.	0.41 *	0.50 **	0.10 <sup>NS</sup>
Panicle length	0.70 **	0.59 **	0.31 <sup>NS</sup>
Spikelets sterility	-0.40 *	-0.51 **	-0.06 <sup>NS</sup>

\*, \*\* Significant at the 0.05 and 0.01 probability levels, respectively.

### Tillering and Dry Matter Production

Year  $\times$  nitrogen (Y $\times$ N) interactions were not significant except at the initiation of panicle growth stage, hence, average values of three years are presented (Table 4). Nitrogen treatment significantly increased tillering. About 67 to 96% of the variation in tillering was apparently due to N fertilization depending on crop growth stage. Tillering increased with the advancement of the crop growth and maximal values were achieved between 35 and 71 days after sowing depending on N rate, and decreased thereafter. Grain yield in cereals is highly dependent upon the number of spike-bearing tillers produced by each plant (20,21). The number of productive tillers depends on environmental conditions during til-



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**Table 4.** Numbers of Tillers in Lowland Rice at Different N Rates During Crop Growth Cycle Across the Three Years

N Rate kg ha <sup>-1</sup>	Days After Sowing					
	22 (IT)	35 (AT)	71 (IP)	97 (B)	112 (F)	140 (PM)
	m <sup>-2</sup>					
0	506	681	652	541	499	468
30	516	749	715	547	516	495
60	574	880	772	601	571	531
90	599	759	751	597	561	522
120	632	876	812	623	573	569
150	619	862	883	660	580	592
180	557	880	903	662	588	572
210	565	819	934	666	590	581
F-test(year)	**	*	**	**	**	**
F-test(N)	*	**	**	**	**	**
F-test(Y × N)	NS	NS	*	NS	NS	NS
CV,%	17	15	10	9	8	9
Regression coefficient						
$\beta_0$	488.7502	690.083	662.4166	533.8749	500.0837	465.4164
$\beta_1$	1.9285	2.4349	1.3960	0.9684	0.9611	1.1329
$\beta_2$	-0.0076	-0.00841	-0.00039	-0.00148	-0.00261	-0.00273
R <sup>2</sup>	0.8211*	0.6658 <sup>NS</sup>	0.9602**	0.9491**	0.9116**	0.9231**

\*, \*\* Significant at the 0.05 and 0.01 probability levels, respectively.

IT, initiation of tillering; AT, active tillering; IP, initiation of panicle; B, booting; F, flowering; PM, physiological maturity.

ler bud initiation and subsequent developmental stages. Numerous studies have shown that tiller appearance, abortion, or both are affected by environmental conditions, especially nutrient deficiencies (20,22,23).

The decrease in tiller number was attributed to the death of some of the last tillers as a result of their failure in competition for light and nutrients (18). Another explanation is that during the period of growth beginning with panicle development, competition for assimilates exists between developing panicles and young tillers. Eventually, growth of many young tillers is suppressed, and they may senesce without producing seed (24). A correlation between grain yield and number of tillers m<sup>-2</sup> at different growth stages was determined (Table 5). Tillering was related significantly with grain yield at all the growth stages, however, highest correlation in all the three years of experimentation was obtained at initiation of panicle growth stage. This means that number of tillers determined at



**Table 5.** Correlation Coefficients (r) Between Lowland Rice Grain Yield and Tiller Number at Different Growth Stages

Parameter	1 <sup>st</sup> Year	2 <sup>nd</sup> Year	3 <sup>rd</sup> Year
Tiller number m <sup>-2</sup> at IT	0.59**	0.41 *	0.23 <sup>NS</sup>
Tiller number m <sup>-2</sup> at AT	0.69**	0.43 *	0.34*
Tiller number m <sup>-2</sup> at IP	0.79**	0.59**	0.68**
Tiller number m <sup>-2</sup> at B	0.67**	0.52**	0.46**
Tiller number m <sup>-2</sup> at F	0.70**	0.37*	0.52**
Tiller number at PM	0.77**	0.48**	0.44*

\*, \*\* Significant at the 0.5 and 0.01 probability levels, respectively.

IT, initiation of tillering; AT, active tillering; IP, initiation of panicle; B, booting; F, flowering; PM, physiological maturity.

this growth stage had more significance than that at any other growth stage in lowland rice.

The Y×N interactions were not significant; therefore, average dry matter yields under different N rates and at different growth stages are presented in Table 6. Nitrogen treatment significantly ( $P<0.01$ ) affected dry matter production at all six growth stages. Regression analysis also showed significant quadratic increases in dry matter production with N application at all growth stages except at initiation of tillering. Dry matter production had a higher correlation with grain yield during booting, flowering and physiological maturity growth stages than at earlier growth stages (Table 7). A relationship between dry matter yield at harvest (PM) and grain yield across the 3 years was determined (Fig. 5). Grain yield increased significantly ( $P<0.01$ ) and quadratically with increasing dry matter. Maximal grain yields of about 6400 kg ha<sup>-1</sup> were achieved at about 9000 kg ha<sup>-1</sup> of dry matter production (Fig. 5), with a harvest index of about 0.42. Grain yield in cereals is related to biological yield and harvest index (25). The biological yield of a cereal crop is the total yield of plant tops and is an indication of the yield of the photosynthetic capability of a crop (7). Harvest index is the ratio of grain to the aboveground biological yield. Grain yield or economic yield can be increased either by increasing total dry matter production or by increasing harvest index. Some authors have speculated that a further increase in grain yield in cereals such as rice through breeding can only be accomplished with an increase in total biological yield (26) and thus total straw yield. The highest harvest index exhibited by California lowland rice cultivars under direct seeding was 0.59 (27). Harvest index obtained in our study is within the range of 0.40 to 0.49 reported by Yoshida (7) for lowland rice cultivars.

Dry matter yield increased with advancement of plant age from initiation of tillering until flowering and then decreased (Table 6). A regression equation was



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**Table 6.** Dry Matter Yield of Lowland Rice at Different N Rates During Three Years

N Rate	Days After Sowing					
	22 (IT)	35 (AT)	71 (IP)	97 (B)	112 (F)	140 (PM)
	kg ha <sup>-1</sup>					
0	313	815	3065	5650	7694	5278
30	320	860	3709	6913	8953	6764
60	342	1230	3721	8242	11056	7294
90	374	1044	4164	8695	10758	7303
120	380	1229	4313	9570	13378	8215
150	452	1207	4893	10031	12745	8624
180	351	1294	5077	11290	13682	9060
210	351	1130	5841	10384	13490	9423
Average	360	1101	4348	8847	11470	7745
F-test (year)	**	**	**	**	*	**
F-test (N)	**	**	**	**	**	*8
F-test(Y × N)	NS	NS	NS	NS	NS	NS
CV,%	24	22	21	22	19	17
Regression coefficient						
$\beta_0$	294.1251	792.8751	3221.375	5639.872	7591.831	5578.044
$\beta_1$	1.4573	5.8196	7.8506	46.1213	57.9223	27.1993
$\beta_2$	-0.0055	-0.0192	-0.01918	-0.1038	-0.1399	-0.0437
R <sup>2</sup>	0.5647 <sup>NS</sup>	0.7555*	0.9719**	0.9676**	0.9416**	0.9647**

\*, \*\* Significant at the 0.05 and 0.01 probability levels, respectively.

IT, initiation of tillering; AT, active tillering; IP, initiation of panicle; B, booting; F, flowering; PM, physiological maturity.

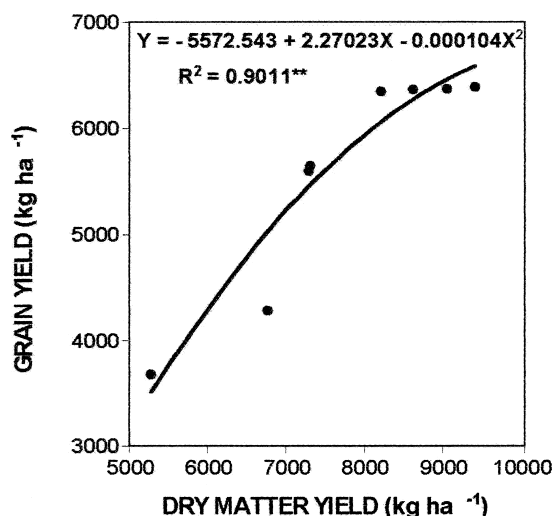
**Table 7.** Correlation Coefficients (r) Between Lowland Rice Grain Yield and Dry Matter Production During Different Growth Stages

Parameter	1 <sup>st</sup> Year	2 <sup>nd</sup> Year	3 <sup>rd</sup> Year
Dry matter yield at IT	0.36*	0.37*	0.29 <sup>NS</sup>
Dry matter yield at AT	0.71**	0.55**	0.42*
Dry matter yield at IP	0.63**	0.51**	0.63**
Dry matter yield at B	0.72**	0.81**	0.61**
Dry matter yield at F	0.81**	0.80**	0.57**
Dry matter yield at PM	0.78**	0.80**	0.53**

\*, \*\* Significant at the 0.05 and 0.01 probability levels, respectively.

IT, initiation of tillering; AT, active tillering; IP, initiation of panicle; B, booting; F, flowering; PM, physiological maturity.





**Figure 5.** Relationship between dry matter yield at harvest and grain yield of lowland rice. Data are averages for three years.

calculated relating age of plants (X) and dry matter yield (Y) at successive growth stages across the N rates. The equation was significant and quadratic ( $Y = -5138.663 + 225.9447X - 0.8917X^2$ ,  $R^2 = 0.93^*$ ). Based on this regression equation, dry matter yield increased up to 126 days of crop growth having a growth cycle of 140 days. The increase in dry matter at this growth period is mainly attributed to higher photosynthesis due to an increase in the leaf area (28). When the increase was compared at successive growth stages, the increase was 206% at the active tillering growth stage as compared to initiation of tillering (IT) across the N rates. Similarly, the increase at the initiation of panicle (IP) growth stage was 295% as compared to active tillering (AT) growth stage across N rates. The increase in dry matter yield was 103% at booting (B) growth stage as compared to initiation of panicle (IP) growth stage. Across the N rates, there was a decrease of 48% in dry matter yield at the physiological maturity (PM) growth stage as compared to flowering (F) growth stage. Dry matter loss from the vegetative tissues during the interval from flowering to maturity suggested active translocation of assimilates to the panicles (18,29), which resulted in a grain yield of about 6400 kg ha<sup>-1</sup> (Fig. 1). The decrease in dry matter shortly before maturity can also be partially explained by the senescence of the lower leaves (30). According to Guindo et al. (31) leaf development contributes the greatest increment to dry matter production.



### Nitrogen Uptake and Use Efficiency

The pattern of N uptake in dry matter of lowland rice under different N rates at different growth stages averaged across years is presented in Table 8. Nitrogen treatment significantly ( $P < 0.01$ ) affected dry matter production at all the growth stages during the crop growth cycle. Regression analysis (Table 8) showed a highly significant ( $P < 0.01$ ) quadratic response of dry matter in relation to N rates at various growth stages. This increase in N uptake is related to dry matter production (Table 6). Similar responses of rice crop to N uptake have been reported by Guindo et al. (29,31) during different stages of development. Nitrogen uptake increased with the advancement of the age of the crop up to the flowering growth

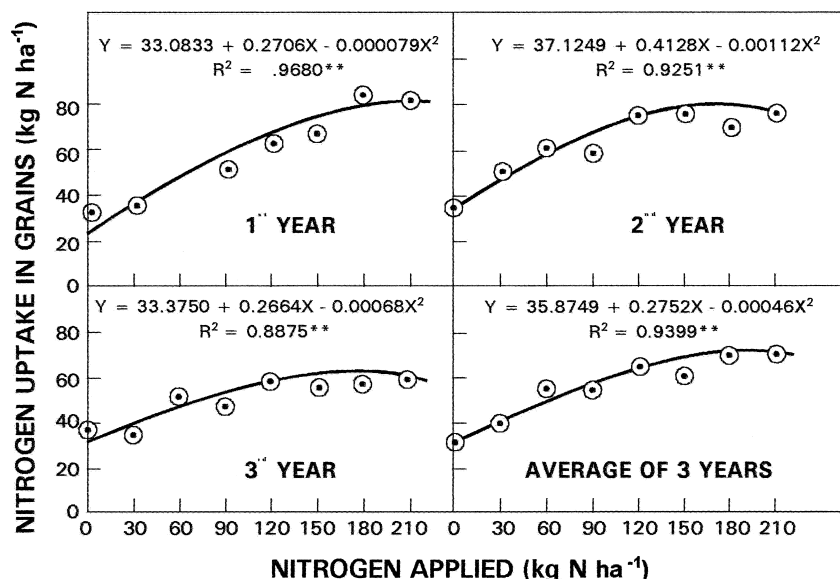
**Table 8.** Nitrogen Accumulation in Dry Matter of Lowland Rice Under Different N Rates During Crop Growth Cycle Across the 3 Years

N Rate	Days After Sowing					
	22 (IT)	35 (AT)	71 (IP)	97 (B)	112 (F)	140 (PM)
	kg ha <sup>-1</sup>					
0	13	24	35	50	57	28
30	13	26	41	62	66	37
60	15	37	45	82	95	40
90	17	33	52	88	89	41
120	17	42	57	91	122	48
150	19	40	63	113	113	52
180	19	40	63	113	113	52
210	16	39	87	130	130	66
Average	16	36	56	94	101	46
F-test (Y)	**	**	**	**	**	**
F-test (N)	**	**	**	**	**	**
F-test(Y x N)	NS	NS	NS	NS	NS	NS
CV, %	23	23	23	23	24	22
Regression Coefficient						
$\beta_0$	12.0833	22.7916	36.7083	50.2916	54.5416	30.2916
$\beta_1$	0.0746	0.2164	0.0903	0.4383	0.6089	0.1204
$\beta_2$	-0.00026	-0.000628	0.000615	-0.000138	-0.00111	0.00021
R <sup>2</sup>	0.7870*	0.8567**	0.9674**	0.9512**	0.9223**	0.9791**

\*, \*\* Significant at the 0.05 and 0.01 probability levels, respectively.

IT, initiation of tillering; AT, active tillering; IP, initiation of panicle; B, booting; F, flowering; PM, physiological maturity.

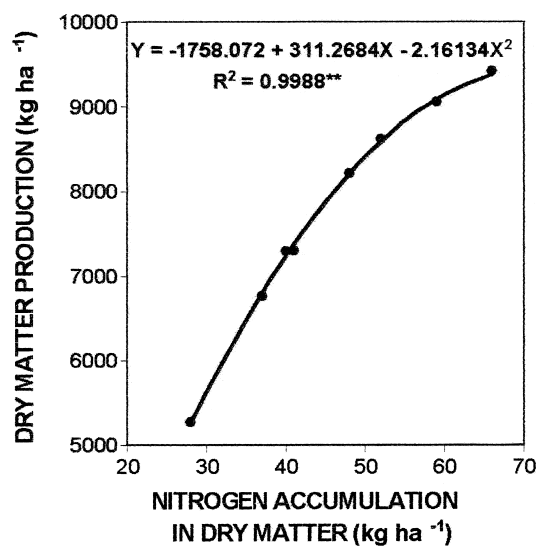




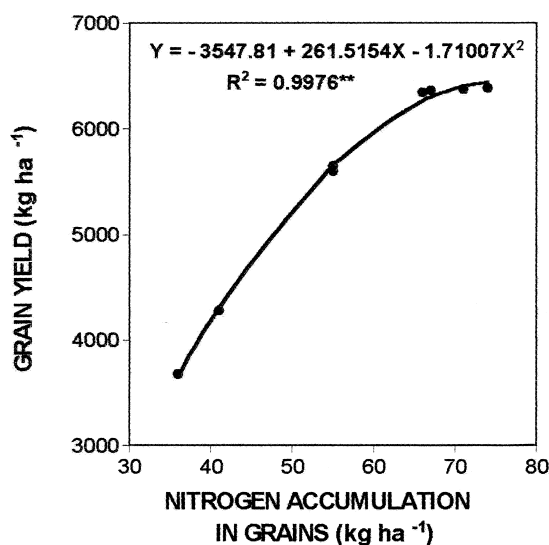
**Figure 6.** Nitrogen uptake in lowland rice grains under different N treatments during the 3 years of experimentation.

stage and decreased thereafter. The increase in N uptake at 35 days after sowing (AT) was 125% as compared to 22 days (IP) after sowing. At 71 (IP) days after sowing, the increase across the N rates was 56% as compared to 35 days (AT) days after sowing. At 97 (B) days after sowing, the increase in N uptake was 68% as compared to 71 (IP) days after sowing. At the 112 days (F) after sowing the N uptake increase across N rates was only 7% as compared to 97 (B) days after sowing. At harvest (140 days after sowing) there was a 77% decrease in N uptake as compared to 112 days after sowing days (F) growth stage. This decrease is related to N translocation to grains at harvest. The Y×N interaction in relation to N uptake in the grains was significant, therefore, 3 years data of N uptake in grains are presented (Fig. 6). Nitrogen uptake was highly significant ( $P < 0.01$ ) and quadratic during the 3 years of experimentation. This quadratic response is related to grain yield during the 3 years of experimentation (Fig. 1). A relationship between N accumulation in dry matter and dry matter yield and N accumulation in grains and grain yield was determined (Figs. 7 and 8). The relationships were significant and quadratic in both the cases. Based on the regression equation, accumulation of 72 kg N ha<sup>-1</sup> produced 9449 kg ha<sup>-1</sup> of dry matter and accumulation of 76 kg N ha<sup>-1</sup> produced 6450 kg ha<sup>-1</sup> grains. These results showed that dry matter as well as grain yield depend on N accumulation in rice plant but up to a certain





**Figure 7.** Relationship between N accumulation in dry matter and dry matter yield of lowland rice across the 3 years.



**Figure 8.** Relationship between N accumulation in grain and grain yield of lowland rice across the 3 years.



limit. After that limit there is no more increase in dry matter or grain yield. At harvest, more N was accumulated in grains than in dry matter. This may be explained by the N harvest index (N accumulation in grains/N accumulation in grains plus dry matter). Nitrogen harvest index across the N rates was 0.64. This means that 64% of the absorbed N was translocated to the grains and 36% remained in the dry matter. Dingkuhn et al. (32) reported N harvest index values ranging from 0.60 to 0.72 for three IRRI semidwarf rice cultivars differing in growth duration. Guindo et al. (31) also reported N harvest index values of 0.58 and 0.62 in two lowland rice cultivars.

Nitrogen use efficiency by crop plants has been defined in five different ways in the literature (33). All five N use efficiencies were calculated and are presented in Table 9. All the N use efficiencies were significantly decreased with increasing N rates except physiological efficiency. Across N rates agronomic efficiency was 23 kg grain produced per kg N applied, and physiological efficiency was 146 kg biological yield (straw plus grain) per unit of N accumulated. Agro-physiological efficiency was 63 kg grain produced per kg of N accumulated in the grain and straw across N rates. Apparent recovery efficiency was 39% and utilization efficiency was 58 kg grain produced per kg of N utilized across N rates.

Agronomic efficiency in lowland rice in the tropics is reported to be in the range of 15 to 25 kg grain produced per kg of applied N (7). Results of the our

**Table 9.** Nitrogen Use Efficiencies Under Different N Rates Across the Three Years

N Rate kg ha <sup>-1</sup>	Agronomic Efficiency kg kg <sup>-1</sup>	Physiological Efficiency kg kg <sup>-1</sup>	Agrophysio- logical Efficiency kg kg <sup>-1</sup>	Apparent Recovery Efficiency %	Utilization Efficiency Kg kg <sup>-1</sup>
30	35	156	72	49	76
60	32	166	73	50	83
90	22	182	75	37	67
120	22	132	66	38	50
150	18	146	57	34	50
180	16	126	51	33	42
210	13	113	46	32	36
Average	23	146	63	39	58
Regression coefficient					
$\beta_0$	37.1228	180.8571	82.8571	51.5714	89.00
$\beta_1$	-0.1214	-0.2916	-0.1666	-0.1047	-0.2607
R <sup>2</sup>	0.9292*	0.6162 <sup>NS</sup>	0.8723*	0.8226*	0.9025**

\*, \*\* Significant at the 0.05 and 0.01 probability levels, respectively.

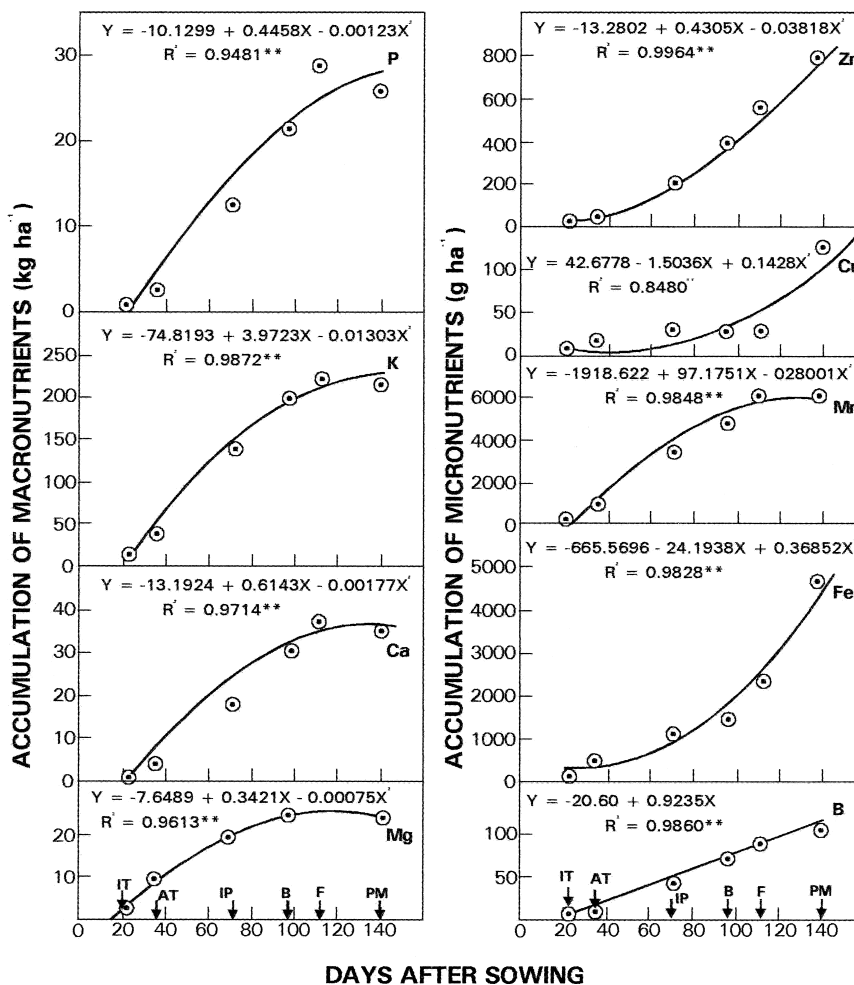


study are within this range. Higher physiological efficiency ( $146 \text{ kg kg}^{-1}$ ) as compared to agrophysiological efficiency ( $63 \text{ kg kg}^{-1}$ ) across the N rates may be due to inclusion of dry matter in calculating this efficiency. Singh et al. (17) reported an agrophysiological efficiency of about  $64 \text{ kg grain per kg of N uptake}$  and agronomic efficiency of  $37 \text{ kg grain per kg of N applied}$  in 20 lowland rice genotypes. An apparent recovery efficiency of 39% across N rates is quite low. The percentage of N recovery varies with soil properties, methods, amounts, and timing of fertilizer applications and other management practices. It usually ranges from 30 to 50% in the tropics (34). Studies conducted in the southern USA on the influence that different application timings and N management strategies have on N use efficiency in rice showed recovery at maturity of 17 to 61% of the applied N (35,36). Singh et al. (17) reported a N recovery efficiency of 37% in 20 lowland rice genotypes. Our results are within this limit. The low N recovery efficiency in lowland rice may be related to N losses from soil via nitrification-denitrification,  $\text{NH}_3$  volatilization, or leaching (37). The efficiency of utilization for grain production in the tropics is about  $50 \text{ kg grain per kg N absorbed}$ , and this efficiency appears to be almost constant regardless of the rice yields achieved (7). Our results of  $58 \text{ kg grain per kg N absorbed}$  across the N rates fall within this limit.

### Nutrient Uptake at Different Growth Stages

Grain yield was significantly and quadratically increased with increasing N rates as determined by regression equations during three years of experimentation. Therefore, nutrient uptakes were determined at maximum N rate ( $210 \text{ kg N ha}^{-1}$ ). Progressive accumulations of P, K, Ca, Mg, Zn, Cu, Mn, Fe, and B during the crop growth cycle are presented in Fig. 9. Accumulation of these nutrients in the straw and grains increased significantly ( $P < 0.01$ ) with age, except the Cu and followed quadratic responses. Only accumulation of B was linear with the advancement of the age of the crop. The accumulation pattern of nutrients was similar to that of dry matter accumulation. The quality of nutrients accumulated was in the order of  $\text{K} > \text{Ca} > \text{P} > \text{Mg} > \text{Mn} > \text{Fe} > \text{Zn} > \text{Cu} > \text{B}$ . Similar nutrient accumulation results were reported by Fageria and Baligar (15) and Fageria et al. (18) in lowland rice crops. At the time of harvest, the proportion of total plant nutrients removed in grain was: 53% N, 55% P, 9% K, 13% Ca, 32% Mg, 26% Zn, 83% Cu, 11% Fe, 6% Mn, and 34% B across the 3 years. De Datta and Mikkelsen (38) reported more or less similar quantities of these nutrients exported to lowland rice grains. To produce one ton of grain, the rice crop removed 22 kg N, 4 kg P, 34 kg K, 6 kg Ca, 4 kg Mg, 133g Zn, 20 g Cu, 724 g Fe, 935 g Mn, and 16 g B in the grains plus straw. Fageria et al. (18) also reported more or less similar quantities of these nutrients removed in grains and straw to produce one ton of grains in lowland rice crop grown on an Inceptisol.





**Figure 9.** Nutrient accumulation in straw and grains of lowland rice crop during the growth cycle at 210 kg N ha<sup>-1</sup>.

### Soil Chemical Properties

Some soil chemical properties at 0–20 cm soil depth were determined after the harvest of the third crop to evaluate soil fertility status of the experimental area after three successive rice crops under different N rates (Table 10). Soil pH was significantly decreased at higher N rates. A regression equation calculated in re-



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**Table 10.** Some Soil Chemical Properties Determined After Harvest of 3<sup>rd</sup> Rice Crop at 0–20 cm Soil Depth Under Different N Treatments

N Rate kg ha <sup>-1</sup>	pH H <sub>2</sub> O	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Al <sup>3+</sup>	H + Al	P	K	O.M.
		cmol <sub>c</sub> kg <sup>-1</sup>				mg kg <sup>-1</sup>		g kg <sup>-1</sup>
0	5.5	2.3	1.5	1.0	10.9	26.1	25	26
30	5.5	2.2	1.6	0.9	10.4	26.0	28	20
60	5.5	2.2	1.6	0.9	12.4	25.7	29	28
90	5.4	1.9	1.5	1.2	13.5	26.2	25	22
120	5.4	2.3	1.5	0.8	13.1	22.1	20	34
150	5.4	1.8	1.4	1.2	11.3	24.6	25	25
180	5.3	1.7	1.1	1.4	10.3	25.6	25	20
210	5.2	1.4	1.3	1.6	10.5	25.7	26	17
Average	5.4	2.0	1.4	1.1	11.6	25.3	25	24
Initial value	5.5	3.7	1.7	0.3	12.3	19.2	38.0	26
F-test	**	NS	NS	Ns	Ns	Ns	Ns	NS
CV,%	1	31	18	35	19	20	16	39
Regression analysis	Q**	Q*	NS	L*	NS	NS	NS	NS

\*, \*\* Significant at the 0.05 and 0.01 probability levels, respectively. Q = Quadratic and L = Linear equations.

lation to N rates (X) and soil pH (Y) was quadratic and highly significant ( $Y = 5.50 + 0.000039X - 0.000066X^2$ ,  $R^2 = 0.9347^{**}$ ). At the 210 kg N ha<sup>-1</sup> rate, pH decrease was about 6% as compared to control treatment of N. This pH decrease is related to use of ammonium sulfate as a source of N fertilizer (39). The use of ammonium sulfate as a source of N is justified due to low level of sulfur in Brazilian Inceptisols (40). Further, rice is extremely tolerant to soil acidity and its yield is not affected adversely at 5.2 soil pH (41), the lowest value achieved in our experimentations. In addition, maximal N rate to achieve 90% of the maximal grain yield was 120 kg N ha<sup>-1</sup>. At this level the soil pH was reduced only from 5.5 to 5.4 (Table 10) after three years of rice cultivation. This means that ammonium sulfate can be used safely as a N source on these soils for rice cultivation.

Calcium level was another soil chemical property that was significantly affected by N rates as evaluated by regression analysis ( $Y = 2.2416 + 0.00063X - 0.000021X^2$ ,  $R^2 = 0.8073^*$ ). The level of this nutrient in the soil decreased at higher N rates. At 210 Kg N ha<sup>-1</sup>, the decrease in Ca level was 64% as compared to control treatment. This may be related to crop removal of this nutrient. Potassium level was not affected by N rates, but was reduced substantially when compared with the original soil level. The K level was also lower than the accepted



critical level which is about  $60 \text{ mg kg}^{-1}$  in Brazilian Inceptisols for lowland rice (15). The reduction in K level may be related to removal of large amounts of this nutrient in plant straw. The experimental plots were harvested and threshed manually, hence a large part of the straw was removed from the experimental area and it was not returned. Aluminum concentration was another soil chemical property that changed significantly under different N treatments. It significantly increased with increasing N rates ( $Y = 0.825 + 0.00285X$ ,  $R^2 = 0.5761^*$ ) after three rice crops. The Al level was also substantially increased as compared to original soil level. Increased aluminum level, however, was not harmful for rice. Fageria and Santos (41) reported that increasing Al level to  $1.5 \text{ cmol}_c \text{ kg}^{-1}$  increased lowland rice yield in Brazilian acid lowland soil, but common bean yield was significantly decreased at this Al level. Therefore, if some legume crops are planted on these soils in rotation with lowland rice during the dry period, care should be taken for Al toxicity. The increase in Al level after harvest of three rice crops may be related to reduction in Ca, Mg, and K levels and decreased in soil pH. Aluminum level in soil solution increased with decreasing basic cations and soil pH (39).

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